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PRELIMINARY FRICTION AND WEAR STUDIES OF COBALT-RHENIUM SOLID SOLUTION ALLOY IN AIR AND IN VACUUM

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16. Abstract

Friction and wear were measured for a cobalt-rhenium solid solution alloy with 12 weight percent rhenium in both air and vacuum at temperatures to 675° C (1247° F). Friction coefficients for the alloy in vacuum were low (0.30) to 525° C (977° F); beyond 525° C (977° F), the friction coefficient increased with temperature to 1.2 at 675° C because of the crystal transformation from hexagonal-close-packed to face-centered-cubic. Wear at 625° C (1157° F) in vacuum was 200 times higher than at 20° C, where the alloy has a stable hexagonal-close-packed structure. The alloy exhibited slightly higher friction in air at 20° C (68° F), but friction decreased linearly with temperature, because of formation of low shear strength oxides, to a value less than 0.20 at 625° C (1157° F).

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SUMMARY

A cobalt-rhenium (Co-Re) solid solution alloy with 12 weight percent rhenium was tested in both air and vacuum in sliding friction experiments to establish preliminary friction and wear data for this system. The experiments were conducted by utilizing a radiused rider sliding against a flat rotating disk in both air and vacuum at temperatures from 20° to 675° C (68° to 1247° F). Phase diagrams for the Co-Re system indicate that additions of rhenium to cobalt will increase the hexagonal-close-packed (hcp) to face-centered-cubic (fcc) crystal transformation temperature, thus maintaining the lower friction and wear of the hcp structure to higher temperatures in vacuum. Friction results showed that the Co - 12-weight-percent-Re alloy sliding on itself in vacuum exhibited low friction coefficient (0.30) to temperatures of 525° C (977° F). Beyond 525° C (977° F), friction increased with temperature to a value of 1.2 at 675° C. This increase in friction is associated with the transformation from hcp to fcc. A comparison of wear values shows that the wear for the cobalt-rhenium alloy at 625° C (1157° F), where the crystal transformation is occurring, is 200 times higher than that measured at 20° C (61° F), where the alloy has a stable hcp structure.

Friction and wear data taken in air show that at 20° C (68° F) the friction coefficient is slightly higher (0.40) than at the same temperature in vacuum (0.30); however, wear was comparable. At temperatures to 625° C (1157° F) in air, friction coefficient decreased linearly with temperature to a value less than 0.20 at 625° C (1157° F). This reduction is attributed to the formation of low shear strength oxide films at increased temperature.

Further additions of rhenium to cobalt are expected to further increase the hcp to fcc crystal transformation temperature, and alloys with higher rhenium concentrations will be investigated.

INTRODUCTION

The influence of crystal structure on friction, adhesion, and wear has been studied by several investigators (refs. 1 to 4). Some of the earliest work on crystal structure effects, done in this laboratory, demonstrated that the hexagonal-close-packed (hcp) structure in general is preferred to the cubic structures with regard to the friction, adhesion, and wear of metals. The superior friction properties for the hcp metals, particularly when the stacking ratios are close to ideal, is attributed to the basel slip mechanism (ref. 1).

The metals cobalt and rhenium both possess the hcp structure and have stacking ratios very close to ideal (c/a lattice ratio of 1.633). Both cobalt and rhenium exhibit low friction and wear in vacuum in the hcp state (ref. 1). Cobalt, however, undergoes a crystal transformation (polymorphism) to the face-centered-cubic (fcc) structure at temperatures above 400° C (ref. 5). Friction studies in vacuum with pure cobalt have shown that a marked increase in both friction and wear of cobalt occurs as the crystal structure transforms from hcp to fcc. The higher friction and wear in the cubic structure is due to the larger number of slip systems in the fcc structure and the increase in shear strength due to the interaction of these slip systems (ref. 3).

Various alloying agents have been added to cobalt to inhibit the crystal transformation or to increase the transformation temperature. Cobalt-molybdenum alloys have been made which possess good friction and wear properties in vacuum (ref. 3). The work described in reference 6 added beryllium to cobalt to form an age-hardenable alloy with an increased temperature range over cobalt but exhibiting a pronounced polymorphic hysteresis.

Rhenium added to cobalt forms a continuous series of simple solid solutions with a corresponding increase in the hcp to fcc transformation temperature that is approximately linear with increasing concentration of rhenium (ref. 7).

The purpose of this investigation was to examine the friction and wear properties of a cobalt-rhenium (Co-Re) solid solution alloy. A cobalt-rhenium alloy with 12 weight percent rhenium was prepared to establish the preliminary friction and wear properties of this system. The friction and wear for a Co - 12-weight-percent-Re friction couple were measured in air and vacuum at temperatures to 675° C. The friction tests were conducted by utilizing a hemispherically tipped rider sliding against a flat rotating disk specimen in both air and vacuum.

ALLOY PREPARATION

The cobalt-rhenium alloys were prepared by powder-metallurgy methods. Cobalt and rhenium powders, less than -200 mesh, were blended in the appropriate percentage. The powder compact was pressed at 35 kilograms per square millimeter and sintered in a hydrogen atmosphere at 1300° C for 16 hours. The pressed compacts were then forged at 1200° C to obtain a density of approximately 95 percent of theoretical with a reduction of about 20 percent. Following forging, the compacts were stress relieved at 1200° C for 30 minutes. Structural photomicrographs were taken, and a typical photomicrograph is shown in figure 1. The photomicrograph shows a one-phase structure. Friction test specimens were then machined from the alloy compacts. X-ray diffraction of the alloy confirmed the hcp structure.

APPARATUS AND PROCEDURE

The friction and wear apparatus used for the alloy friction studies is shown in figure 2. A 6.3-centimeter disk specimen is mounted on the end of a vertical drive shaft. The drive shaft is supported by two molybdenum disulfide lubricated angular contact ball bearings and is driven by a magnetic coupling arrangement. One 20-pole circular magnet is mounted inside the chamber on the end of the shaft opposite the disk specimen. The other 20-pole magnet is mounted outside the chamber. The magnet faces are separated by a thin stainless-steel diaphragm for vacuum sealing. The outer magnet is driven by a variable-speed electric motor. The 0.376-centimeter radiused rider specimen is held in an Inconel holder which bolts to a bellows-sealed, gimbal-mounted load arm. The load arm is used to apply the normal specimen load by the application of weights external to the chamber. The friction force is transmitted by the arm to a strain-gage assembly mounted outside the chamber wall. The strain-gage output is read on a strip-chart recorder which is calibrated in friction force units.

Specimen heating for the vacuum runs was accomplished by a 1.5-kilovolt-ampere electron gun which was mounted below the disk specimen, adjacent to the rider holder. The specimen temperature was measured by a Chromel-Alumel thermocouple welded on the tip of the rider near the point of rider-disk contact. The thermocouple signal was fed into a ratio controller which varied the electron gun filament on-off time to maintain the test temperature to within 20° C.

For the high-temperature air run, a low-frequency induction coil, which surrounded the disk circumferentially, was used for heating. Test temperatures were read by a thermocouple and also by infrared pyrometry.

The vacuum system consisted of two sorption forepumps and a 400-liter-per-second ion pump (0.4-m^3/sec). A liquid-nitrogen-cooled titanium getter pump was also employed. After a 24-hour bakeout at 150° C, the pressure was in the range of 10^{-9} to 10^{-10} torr. When elevated temperatures were used, the pressure increased to the

10^{-7} to 10^{-8} torr range at maximum test temperatures.

The rider and disk specimens were machine ground to a root-mean-square finish of 4 to 8. Prior to insertion into the vacuum chamber, they were rinsed with acetone and washed with hot tap water and detergent. Following washing, the specimens were scrubbed with moist levigated alumina, rinsed with distilled water, rinsed with reagent grade ethyl alcohol, and dried.

RESULTS AND DISCUSSION

The addition of rhenium to cobalt was expected, in view of the phase diagrams for the cobalt-rhenium system, to inhibit the hcp to fcc crystal transformation, and consequently to maintain the low friction and wear properties of the nearly ideal hcp structure to higher temperatures than pure cobalt. The addition of rhenium was also expected to improve the mechanical properties of the alloy as compared to pure cobalt. The hardness of the Co - 12-weight-percent-Re alloy was Rockwell C-27 to 29, which is higher than for pure cobalt (Rockwell B-76 to 78).

The cobalt-rhenium alloy was first run in vacuum at temperatures to 675° C in order to determine the influence of temperature on the friction of the Co - 12-weight-percent-Re alloy and to compare data for the alloy with those for pure cobalt. The results are shown in figure 3. Also shown in figure 3 are data for pure cobalt under similar conditions. The Co - 12-weight-percent Re alloy exhibited a low friction coefficient ($F_k \sim 0.3$) at temperatures to 525° C. This level of friction is very close to that of pure cobalt at low temperatures. At 575° C and beyond, the friction increased continuously with temperature until at 675° C a friction coefficient of 1.2 was measured. Pure cobalt, however, shows a sharp rise in friction at temperatures beyond 325° C, and at 425° C the friction coefficient for pure cobalt was 0.50, while for the alloy, the friction coefficient was still around 0.3. For both the pure cobalt and the cobalt-rhenium alloy, the increase in friction with temperature can mainly be attributed to the transition from the hcp to the fcc structure.

Figure 4 presents photographs of the rider and disk wear areas of the alloy couple after a wear run for 1 hour at 20° C in vacuum. At this temperature, the alloy is hcp and shows low rider and disk wear. The disk wear track is relatively smooth and is characterized by plastic flow in the wear track.

In figure 5, photographs of the rider and disk wear scars are shown after a 1-hour wear run at 625° C in vacuum. At this temperature, the alloy is in the transition from hcp to fcc. The wear areas are characterized by the adhesive transfer of metal from one surface to the other. This adhesive transfer is characteristic of the pure cubic metals. The friction coefficient during the 1-hour run was relatively constant at 1.2 to

1.3. The wear volume of the rider run at 625° C is more than 200 times that run at 20° C.

Figure 6 presents wear photographs for the cobalt-rhenium alloy after a 1-hour wear run at 20° C in air. The friction coefficient for the air run averaged 0.40, which is slightly higher than that for vacuum (0.30), although the wear was comparable to that measured in vacuum. Small patches of dark deposits can be seen in both the rider and disk wear photographs. These deposits, although not analyzed, were probably oxide formed at the interface by frictional heating.

Figure 7 shows surface profile tracings across the disk wear track after 1-hour wear runs in vacuum at 20° and 625° C and in air at 20° C. The surface profile tracings show well the contrast between the wear mechanism at 20° and 625° C in vacuum. The wear track for the air run shows a narrow and deeper wear track than that for vacuum, and the difference is probably due to an abrasive effect of the oxide formed at the interface during sliding.

In order to determine if the hcp to fcc transformation could be observed in air and consequently in the presence of surface oxides, a friction run was made with the Co - 12-weight-percent-Re alloy at temperatures to 625° C in air. The results are shown in figure 8. At room temperature, the coefficient of friction is about 0.40; however, with heating to 625° C no increase in friction was observed even at the maximum temperature of 625° C; rather a linear decrease in friction with temperature was observed. Upon cooling it was found that the friction curve followed the heating curve almost exactly. In air, for the Co - 12-weight-percent-Re alloy, the effect of oxide films is markedly more important than substrate structure. After being tested at 625° C, the alloy disk was coated with a thin dark film. The film was examined by X-ray diffraction, but the analysis was inconclusive in that no single cobalt or rhenium oxide could definitely be identified. It is likely that the thin film is a solid solution of cobalt and rhenium oxides. The decrease in friction with temperature is associated with increasing rates of oxidation (e.g., thicker oxide films), replenishment of the film in the wear track, and possible melting of some of the oxide films. Rhenium forms oxides which melt as low as 266° C (ref. 8). Reference 9 indicates that molten oxide films can significantly lower the force required for frictional shear and thus lower friction coefficients.

It is anticipated that further additions of rhenium to cobalt (e.g., 20 or 40 weight percent) will further increase the temperature range of the alloy for sliding friction applications. Alloys with higher concentrations of rhenium will be investigated.

SUMMARY OF RESULTS

Preliminary friction and wear tests conducted with a cobalt - 12-weight-percent-rhenium solid solution alloy yielded the following results:

1. The alloy showed low friction coefficient (0.30) in vacuum to 525° C (977° F). Beyond 525° C (977° F), friction increased with increasing temperature because of the transformation from hexagonal-close-packed (hcp) to face-centered-cubic (fcc). The effect of the crystal transformation on friction occurs at a temperature higher for the alloy than for pure cobalt.

2. The alloy exhibited both low wear and low friction at temperatures where the alloy has the hcp structure. At 625° C (1157° F), where the alloy transforms to fcc, friction increased to four times the room-temperature value and rider wear was 200 times greater.

3. The alloy exhibited a friction coefficient of 0.40 and low wear in air at room temperature. With increasing temperature, friction coefficient decreased linearly to less than 0.20 at 625° C (1157 F).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 4, 1970,
129-03.

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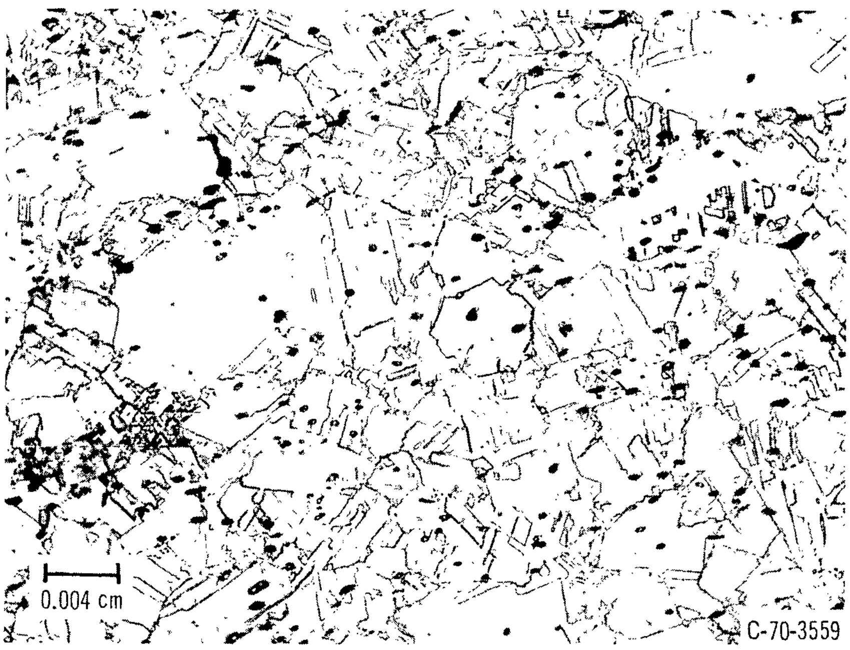


Figure 1. - Photomicrograph of cobalt - 12-weight-percent rhenium alloy.

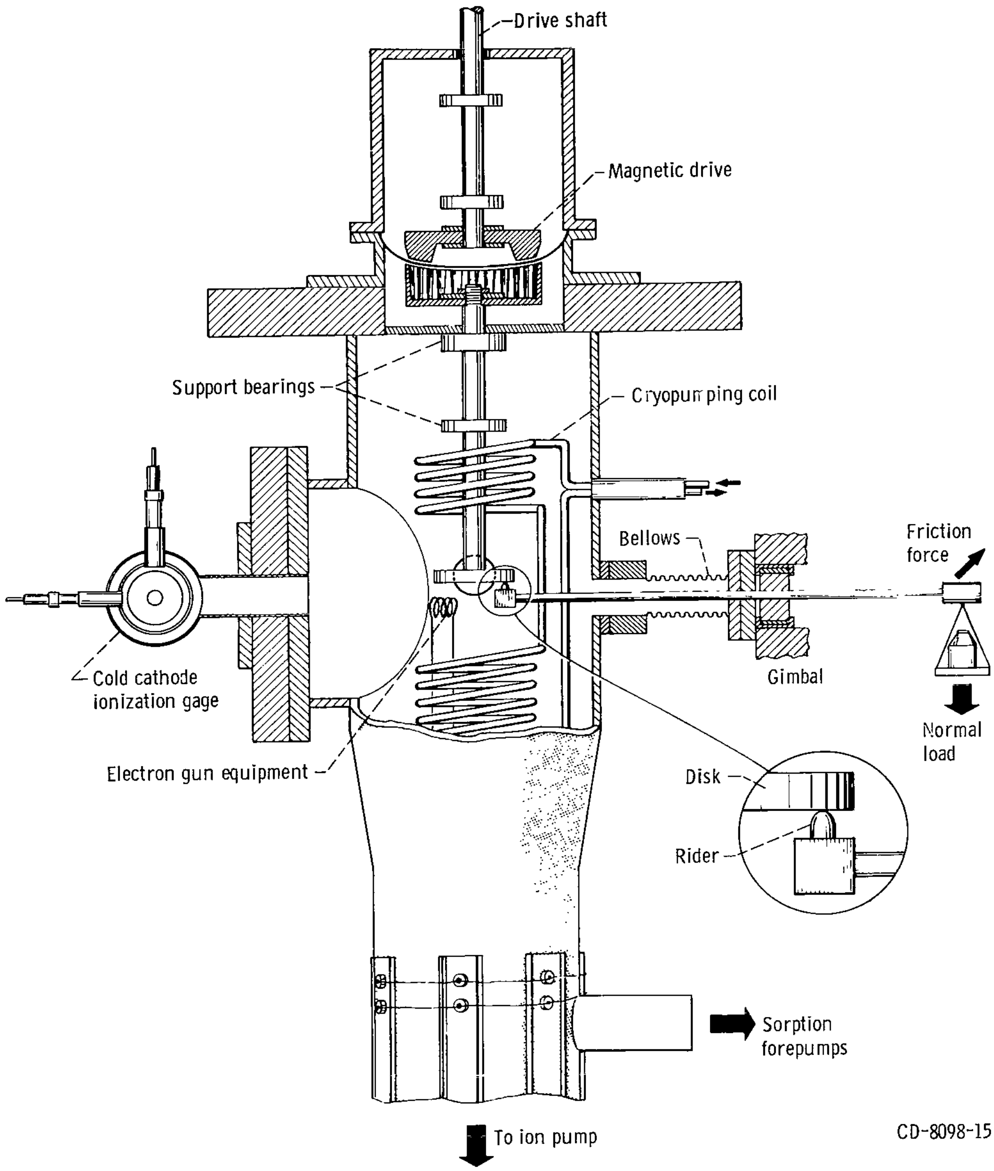


Figure 2. - Vacuum friction apparatus.

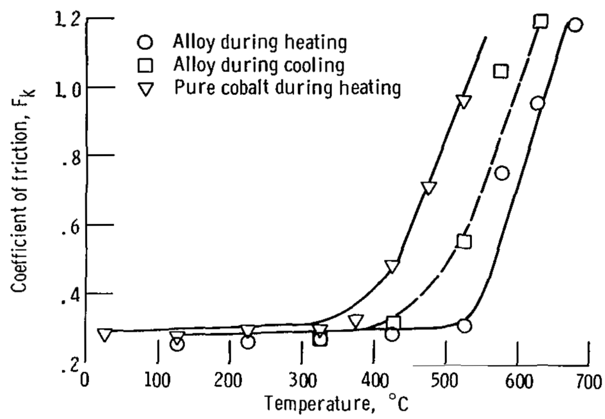
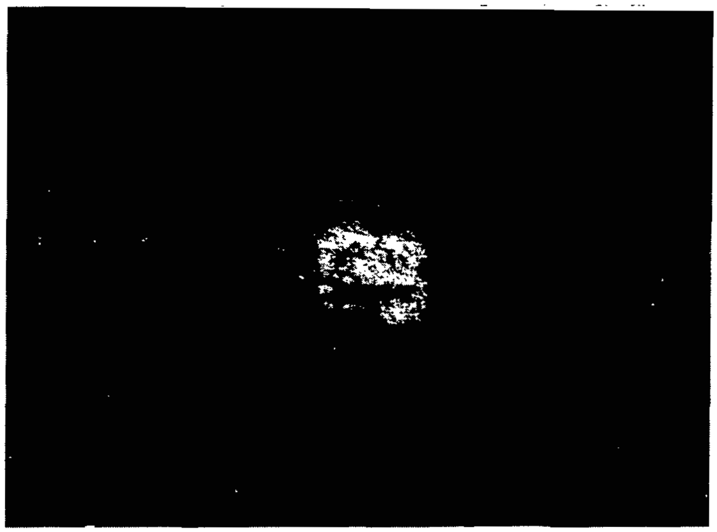
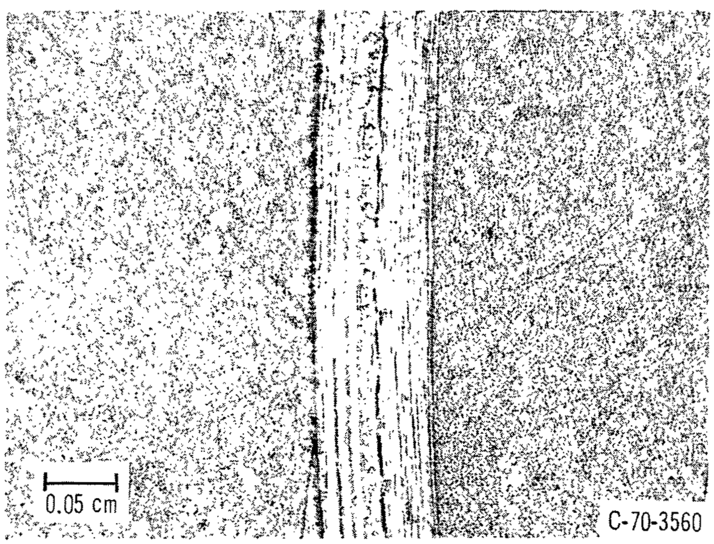


Figure 3. - Coefficient of friction as function of temperature for cobalt - 12 percent rhenium sliding on cobalt - 12 percent rhenium. Pressure, 10^{-9} to 10^{-7} torr; load, 1 kilogram; sliding velocity, 40 feet per minute (12.2 m/min).

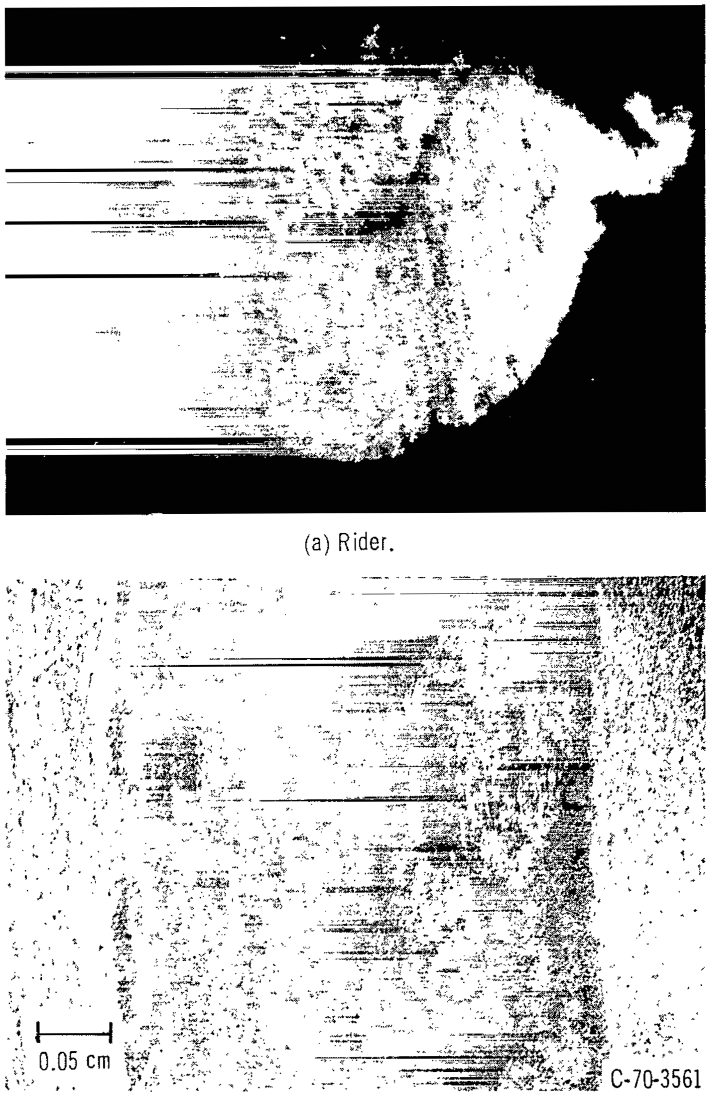


(a) Rider.



(b) Disk.

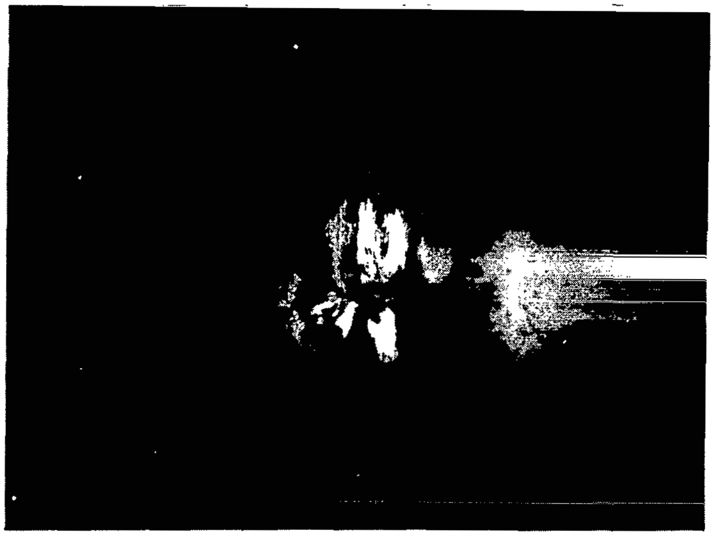
Figure 4. - Rider and disk wear areas. Temperature, 20° C; pressure, 10^{-9} torr; load, 1 kilogram; sliding velocity, 40 feet per minute (12.2 m/min).



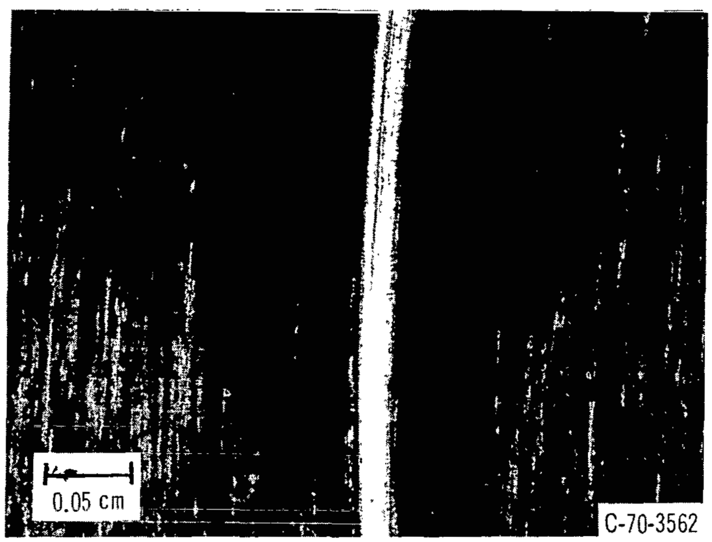
(a) Rider.

(b) Disk.

Figure 5. - Rider and disk wear areas. Temperature, 625° C; pressure 10^{-8} torr; load, 1 kilogram; sliding velocity, 40 feet per minute (12.2 m/min).

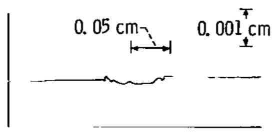


(a) Rider.

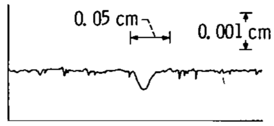


(b) Disk.

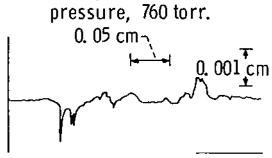
Figure 6. - Rider and disk wear areas. Temperature, 20° C; pressure, 760 torr; load, 1 kilogram, sliding velocity, 40 feet per minute (12.2 m/min).



(a) Temperature, 20° C; pressure, 10^{-9} torr.



(b) Temperature, 20° C; pressure, 760 torr.



(c) Temperature, 625° C; pressure, 10^{-8} torr.

Figure 7. - Surface profile tracings of disk wear track. Load, 1 kilogram; sliding velocity, 40 feet per minute (12.2 m/min).

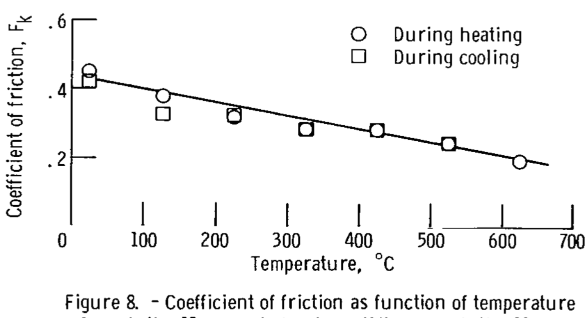


Figure 8. - Coefficient of friction as function of temperature for cobalt - 12 percent rhenium sliding on cobalt - 12 percent rhenium. Pressure, 760 torr; 30 percent relative humidity; load, 1 kilogram; sliding velocity, 50 feet per minute (15.2 m/min).

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